FUZZY LOGIC BASED CONTROL OF VARIABLE SPEED CAGE WIND GENERATION SYSTEM

A

THESIS REPORT

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY

IN

POWER CONTROL & DRIVES

BY

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National Institute of Technology, Rourkela

Rourkela-769008, Orissa

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CERTIFICATE

This is to certify that the work in this thesis report entitled “Fuzzy logic based control of variable speed cage wind generation system”, which has been submitted by **Mrs. Kamaljeet Kaur** bearing roll No.20502029 in the partial fulfillment of the requirement for the award of the degree leading to Master of Technology in specialization in “power control & drives”, department of national institute of technology, Rourkela embodies the results of investigation carried out by her under my supervision and guidance.

To my knowledge the results embodied in this discussion have not been submitted to any other university or institute for award of any degree.

Dr. K.B.Mohanty

Asst. Professor

N.I.T, Rourkela

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KAMALJEET KAUR

ROLL NO-20502029.

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ABSTRACT

The global electrical energy consumption is rising and there is steady increase of the demand on power generation. So in addition to conventional power generation units, a large no. of renewable energy units are being integrated into the power system. A wind electrical generation system is the most cost competitive of all the environmentally clean and safe renewable energy sources in world. The recent evolution of power semiconductors and variable frequency drive technology has aided the acceptance of variable speed generation systems.

Fuzzy logic is a powerful and versatile tool for representing imprecise, ambiguous and vague information. It helps us model difficult, even intractable problems. Advantages of fuzzy control are that it is parameter insensitive, provides fast convergence and accepts noise noisy and inaccurate signals. The fuzzy algorithms are universal and can be applied retroactively in any system.

In this thesis a squirrel cage induction generator feeds power to a double sided pulse width modulated converter system which feeds power to an autonomous load or grid. The generation system has three no.s of fuzzy logic control with vector control in its inner loop.

- The first fuzzy controller tracks the generator speed with the wind velocity to extract maximum power.
- The second fuzzy controller programs the machine flux for light load efficiency improvement .
- The third fuzzy controller gives robust speed control against wind gust and turbine oscillatory torque.

The fuzzy logic based control of the system helps to optimize efficiency and enhance performance. The system gives excellent performance and can easily be translated to a larger size in the field.

LISTS OF FIGURES

CHAPTER 1

INTRODUCTION

Introduction
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1.1 INTRODUCTION

Wind electrical power systems are recently getting lot of attention, because they are cost competitive, environmental clean and safe renewable power source, as compared to fossil fuel and nuclear power generation.

The reason for the world wide interest in developing wind generation plants is the rapidly increasing demand for electrical energy and the consequent depletion of fossil fuels, namely , oil and coal , whose reserves are limited. The depletion reserves, increase in demand, and certain factors in world politics have together contributed to a sharp rise in the cost of thermal power generation. Many places also do not have the potential for generating hydel power. Nuclear power generation was once treated with great optimism, but with the knowledge of the environmental hazards associated with the possible leakage from nuclear power plants, most countries have decided not to install them anymore.

The growing awareness of these problems led to heightened research efforts for developing alternative sources of energy for generation of electricity. The most desirable source would be one that is non- pollutant, available in abundance and renewable and can be harnessed at an acceptable cost in both large – scale and small scale systems. The most promising source satisfying all these requirements is wind, a natural source energy source. Wind energy conversion may be mechanical or electrical in nature, but the present focus is on electricity generation.

The development of wind energy for wind energy for electrical power generation got a boost when, in the early decades of the twentieth century, aviation technology resulted in an improved understanding of the forces acting on the blades moving through air. This resulted in the development of wind turbines with two or three blades. High speed and high efficiency of turbines were the necessary conditions for successful electricity generation. Through the efforts of countless scientists and engineer from various disciplines, wind energy has now matured as an economically viable renewable source of energy.

Wind energy is one of the most available and exploitable forms of renewable energy. Wind blows from a region of higher atmospheric pressure to one of lower atmospheric pressure .The difference in pressure is caused by (a) the fact that earth's surface is not uniformly heated by the sun and (b) the earth's rotation. Wind energy is the by product of solar energy, available in the form of the kinetic energy of air. Wind has been known to man as a natural source of mechanical power for long. The technology of wind power has evolved over this long period. Of the various renewable energy sources, wind energy has emerged as the most viable source of electrical power and is economically competitive with the conventional sources.

The global electrical energy is rising and there is steady rise of the demand on power generation, transmission, distribution and utilization. The maximum extractable energy from the 0-100 m layer of air has been estimated to be the order of 10^{12} KWh/annum, which is of the same order as hydroelectric potential.

The terms "wind energy" or "wind power" describe the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity to power homes, businesses, schools, and the like.

Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow, or motion energy, when "harvested" by modern wind turbines can be used to generate electricity.

Since earliest recorded history, wind power has been used to move ships, grind grain and pump water. There is evidence that wind energy was used to propel boats along the Nile River as early as 5000 B.C. Within several centuries before Christ, simple windmills were used in China to pump water.

In the United States, millions of windmills were erected as the American West was developed during the late 19th century. Most of them were used to pump water for farms and ranches. By 1900, small electric wind systems were developed to generate direct current, but most of these units fell into disuse as inexpensive grid power was extended to rural areas during the 1930s. By 1910, wind turbine generators were producing electricity in many European countries.

Wind turbines, like aircraft propeller blades, turn in the moving air and power an electric generator which supplies an electric current. Modern wind turbines fall into two basic groups; the horizontal-axis variety, like the traditional farm windmills used for pumping water; and the vertical-axis design, like the eggbeater-style Darrieus model, named after its French inventor. Modern wind technology takes advantage of advances in materials, engineering, electronics, and aerodynamics. Wind turbines are often grouped together into a single wind power plant, also known as a wind farm, and generate bulk electrical power.

Electricity from these turbines is fed into the local utility grid and distributes to customers just as it is with conventional power plants.

Wind turbines are available in a variety of sizes, and therefore power ratings. The largest machine, such as the one built in Hawaii, has propellers that span the more than the length of a football field and stands 20 building stories high, and produces enough electricity to power 1400 homes. A small home-sized wind machine has rotors between 8 and 25 feet in diameter and stands upwards of 30 feet and can supply the power needs of an all-electric home or small business.

All electric-generating wind turbines, no matter what size, are comprised of a few basic components: the rotor (the part that actually rotates in the wind), the electrical generator, a speed control system, and a tower. Some wind machines have fail-safe shutdown systems so that if part of the machine fails, the shutdown systems turn the blades out of the wind or puts on brakes.

Just like solar electric systems, wind powered systems can be used in two ways: off-grid or on-grid. Off-grid is when your home or business is entirely disconnected from electric utility company and you generate absolutely all of the electricity you need. Usually these systems cost about 30% more than an on-grid (or 'grid-tie' system). A grid tie wind power system sends all of its electricity back into the public electrical network (grid) which the electric company gives you credits for. At the month, the electric company sums up your credits with how much your home or business has consumed, and if you're lucky the electric company will owe you money! Unfortunately, most electric companies only pay you a small fraction of what they charge you for those extra kilowatt-hours you've created. So it's usually ideal to design a system that very closely offsets how much electricity you consume or just little less, than attempting to make money from the electric company.

Benefits of Wind Power:

A wind energy system can provide a cushion against electric power price increases. Wind energy systems help reduces U.S. dependence on fossil fuels; and they are nonpolluting. If you live in a remote location, a small wind energy system could help you avoid the high costs of having utility power lines extended to your site. Although wind energy systems involve a significant initial investment, they can be competitive with conventional energy sources when you account for a lifetime of reduced or altogether avoided utility costs. The length of the payback period – the time before the savings resulting from your system equal the cost of the system itself – depends on the system you choose, the wind resource on your site, electricity costs in your area, and how you use your wind system.

Small wind energy systems can be used in connection with an electricity transmission and distribution system (called grid-connected systems), or in stand-alone applications that are not connected to the utility grid. A grid-connected wind turbine can reduce consumption of utility-supplied electricity for lighting, appliances, and electric heat. If the turbine cannot deliver the amount of energy you need, the utility makes up the difference. When the wind system produces more electricity than the household requires, the excess can be be returned to the grid. With the interconnections available today, switching takes place automatically. Stand-alone wind energy systems can be appropriate for homes, farms, or even entire communities (a co-housing project, for example) that are far from the nearest utility lines. Either type of system can be practical if the following conditions exist

These are the few requirements of wind generation system:

- Wind generation is dependent on the quality and quantity of the wind hitting the blades. The better the wind you have , the more power you will generate.
- The power available in wind increases by the cube of the wind speed - if wind speed doubles, power output increases by eight.
- Turbulent wind (from obstructions, geographical features, etc.) will reduce the power output as the turbine swings back and forth hunting for the wind.

These are the few requirements of site for wind generation system:

- The higher a turbine, the more power is generated, the better quality the wind.
- A wind turbine should be at least 40 ft above any object within a 400 ft radius. Note there are often exceptions to this rule depending on your site.
- It is often more economical to install a higher tower than purchasing a larger turbine.
- Space: Generally locations with an acre or more will be suitable. Most urban locations will not permit you to install a wind generator in your yard. A guyed tower requires 1/2 the height of the tower as a radius at a minimum for location of anchor points. Space is also required for ground assembly and erection of the tower. Lattice towers require less surface area, but are more complex and expensive to install.

The concept of Fuzzy Logic (FL) was conceived by Lotfi Zadeh, a professor at the University of California at Berkley, and presented not as a control methodology, but as a way of processing data by allowing partial set membership rather than crisp set membership or non-membership. This approach to set theory was not applied to control systems until the 70's due to insufficient small-computer capability prior to that time. Professor Zadeh reasoned that people do not require precise, numerical information input, and yet they are capable of highly adaptive control. If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement.

FL is a problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded micro-controllers to large, networked, multi-channel PC or workstation-based data acquisition and control systems. It can be implemented in hardware, software, or a combination of both. FL provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information. FL's approach to control problems mimics how a person would make decisions, only much faster.

FL offers several unique features that make it a particularly good choice for many control problems.

- It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.
- Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.
- FL is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.
- Because of the rule-based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated, although defining the rulebase quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller FL controllers distributed on the system, each with more limited responsibilities.
- FL can control nonlinear systems that would be difficult or impossible to model mathematically. This opens doors for control systems that would normally be deemed unfeasible for automation.

Linguistic variables are used to represent an FL system's operating parameters. The rule matrix is a simple graphical tool for mapping the FL control system rules. It accommodates two input variables and expresses their logical product (AND) as one output response variable.

Fuzzy Logic provides a completely different, unorthodox way to approach a control problem. This method focuses on what the system should do rather than trying to understand how it works. One can concentrate on solving the problem rather than trying to model the system mathematically, if that is even possible. This almost invariably leads to quicker, cheaper solutions. Once understood, this technology is not difficult to apply and the results are usually quite surprising and pleasing. The future of fuzzy logic is undetermined. There is no limit to where it can go. The future is bright. In other words , the future is fuzzy.

The employment of Fuzzy Control is commendable-

- for very complex processes, when there is no simple mathematical model
- for highly nonlinear processes
- if the processing of (linguistically formulated) expert knowledge is to be performed

The employment of Fuzzy Control is no good idea if-

- conventional control theory yields a satisfying result an easily solvable and adequate mathematical model already exists
- the problem is not solvable

Following are the few examples for Fuzzy Logic applied in reality-

- Automatic control of dam gates for hydroelectric-power plants
- Simplified control of robots
- Camera aiming for the telecast of sporting events
- Substitution of an expert for the assessment of stock exchange activities
- Efficient and stable control of car-engines
- Cruise-control for automobiles
- Improved efficiency and optimized function of industrial control applications
- Positioning of wafer-steppers in the production of semiconductors
- Optimized planning of bus time-tables
- Archiving system for documents
- Prediction system for early recognition of earthquakes
- Medicine technology: cancer diagnosis
- Automatic motor-control for vacuum cleaners with recognition of surface condition and degree of soiling.

This project investigates a close loop control of wind generation system using fuzzy logic control.

1.2 LITERATURE SURVEY

In [1], a variable speed cage wind generation system is used where fuzzy logic principles are used for efficiency optimization and performance enhancement control.a squirrel cage induction generator feeds the power to a double sided pulse width converter system which feeds power to either a utility grid or to an autonomous system. The generation system uses three no.s of fuzzy logic controllers.

[2] describes the control strategy development, design and performance evaluation of wind generation system more elaborately using controller membership functions and rule matrix .

[3] describes the project summary of the generation system.

[4] describes all the fuzzy logic principles required for the generation system. It also help us to understand clearly the application of the principles in fuzzy control of vector drive,flux programming vector - drive for efficiency improvement and fuzzy control of wind generation system.

[5] describes the evaluation of different types of membership functions in fuzzy control of an induction motor drive. Fuzzy controller sensitivity has been analyzed and compared for different membership functions with the triangular function as the base.Results of [5] shows that triangular membership function gives the best drive performance as it consists of simple straight line segments which is very easy to implement in fuzzy control.

[6] explains the different membership function distribution effect on fuzzy logic controllers. Results of [6] also shows that triangular membership function gives the best induction motor drive performance.

[8] explains the role of fuzzy logic controller-I in the generation system with its results. The main function of FLC-I is to search on line the optimum generator speed so that the aerodynamic efficiency of the wind turbine is maximum.

[9] explains the role of fuzzy logic controller-II in the generation system with its results. The main function of FLC-II is to program the machine flux by an on line search so as to optimize the machine converter efficiency.

[10] describes the on line efficiency optimization control of an indirect vector controlled induction motor drive with the help of its results ,which helps to evaluate the performance enhancement of fuzzy controllers in a better way.

1.3 MOTIVATION

The main motivations of this thesis are :

- Availability of conventional energy sources are decreasing day by day.
- Importance of alternative energy investment.
- Requirement of clean and safe renewable energy sources and safety problems of conventional power plants.
- Need to supply an overwhelming industrial growth and the increasing electricity demand of consumers due to increase in population.
- The world has enormous resources of wind power . With only 10% of such potential all the electricity needs would be met.
- Over 1700 MW of wind generators installed worldwide . Current generation of
  6 billion KWh of energy annually.
- Estimated that the generation will grow to 100 billion KWh by the turn of the millennium.
- Recent evolution of power semiconductors and variable frequency drive technology has aided the acceptance of variable speed generation systems .
- Drawback of wind power is that its availability is somewhat statistical in nature.
- Must be supplemented by additional sources to supply the demand curve.
- In spite of additional cost of power electronics and control , the total energy capture in a variable speed wind turbine system is larger and therefore the lifecycle cost is lower than with fixed speed drives.

Motivations of using fuzzy control in wind systems:

- Fuzzy logic is a powerful and versatile tool for representing imprecise, ambiguous and vague information. It helps us model difficult, even intractable problems.
- To change the generator speed adaptively , so as to track the power point as the wind velocity changes. To reduce the generator rotor flux, boosting the machine efficiency when the optimum generator speed set up is attained.
- To have robust speed control against turbine torque pulsation , wind gusts and vortices.

1.4 OBJECTIVE AND THESIS OUTLINE

The main objective of this thesis is to analyze the performance of variable speed wind generation system by using fuzzy logic principles for efficiency optimization and performance enhancement control.

The thesis outlines are:

Chapter -2 deals with wind generation system description. Also the closed loop control of the system has been discussed in brief. Chapter -3 deals with basics of dynamic d-q model, vector control and synchronous current control loop of induction machine. Chapter -4 deals with all the three fuzzy logic controllers with their rule matrices.The first fuzzy controller FLC-1 searches on line the optimum generator speed so that the aerodynamic efficiency of the wind turbine is maximum.The second fuzzy controller FLC-2 programs the machine flux by an on line search so as to optimize the machine converter efficiency.The third fuzzy controller FLC-3 performs robust speed control against turbine oscillatory torque and wind vortex.

CHAPTER 2

WIND TURBINE AND WIND GENERATION SYSTEM

Wind Generation System Description

Wind energy is the by product of solar energy, available in the form of the kinetic energy of air. Wind has been known to man as a natural source of mechanical power for long. The technology of wind power has evolved over this long period. Of the various renewable energy sources, wind energy has emerged as the most viable source of electrical power and is economically competitive with the conventional sources

The global electrical energy is rising and there is steady rise of the demand on power generation , transmission , distribution and utilization. The maximum extractable energy from the 0-100 m layer of air has been estimated to be the order of10^{12} KWh /annum , which is of the same order as hydroelectric potential.

This chapter deals with wind turbine and wind generation system .It also investigates a close loop control of wind generation system using fuzzy logic control.

2.1 WIND GENERATION SYSTEM DESCRIPTION

2.1.1 Converter system

A vertical (or horizontal) wind turbine is coupled to the shaft of a squirrel cage induction generator through a speed up gear ratio . The variable frequency variable voltage power from the generator is rectified by a PWM IGBT rectifier [1]. The rectifier also supplies the excitation need of the machine. Salient advantages of the converter system include the following.

- Line side power factor is unity with no harmonic current injection .
- The cage type induction machine is extremely rugged, reliable, economical, and universally popular.
- Machine current is sinusoidal and no harmonic copper loss.
- Rectifier can generate programmable excitation for the machine.
- Continuous power generation from zero to highest turbine speed is possible.
- Power can flow in either direction permitting the generator to run as a motor for start-up .
- Autonomous operation of the system is possible with either a start-up capacitor or with a battery on the dc link.
- Extremely fast transient response is possible.
- Multiple generators or multiple systems can be operated in parallel.
- The inverter can be operated as a VAR/harmonic compensator when spare capacity is available.

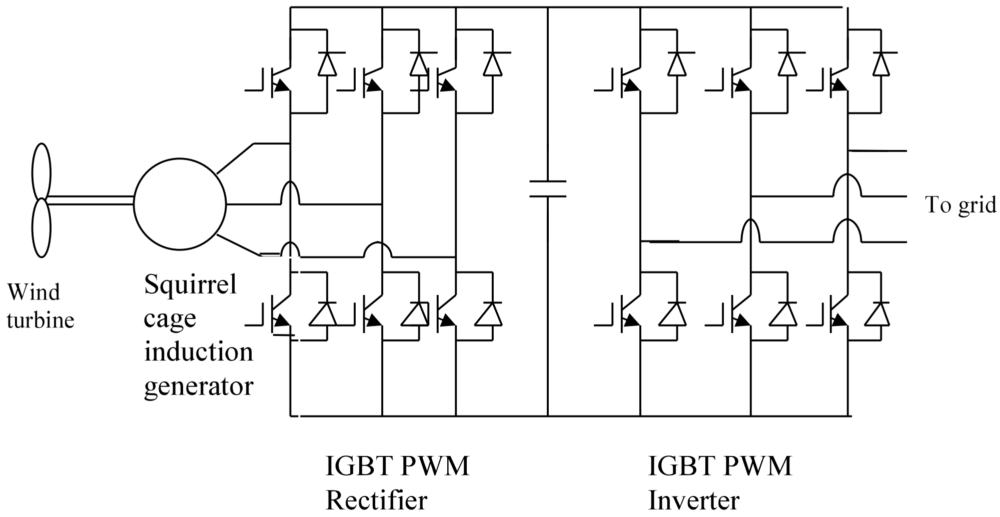

Fig.2.1 A voltage fed double PWM converter wind generation system

2.1.2 Turbine characteristics

Both horizontal and vertical axis wind turbines are used in wind generation systems. The vertical Darrieus type has the advantages of being located on the ground and accepting wind from any direction without any special yaw mechanism. It is, therefore, preferred for high power output. The disadvantages are that the turbine is not self-starting and there is a large pulsating torque which depends on wind velocity, turbine speed, and other factors related to the design of the turbine. [1],[7]The aerodynamic power of a vertical turbine is given by the equation:

$$P = \frac{1}{2} \rho\pi R_{\omega}^{2} V_{\omega}^{3} C_{P} \tag{2.1}$$

where, ρ =air density,

R_{ω} =Turbine radius,

V_{ω} =Wind velocity,

C_p =Turbine power coefficient.

$$\lambda = \frac{R\Omega}{v} \tag{2.2}$$

The aerodynamic torque of a vertical turbine is given by the equation:

$$T_m = C_p(\lambda) \frac{0.5\rho\pi R_{\omega}^{3}}{\eta_{GEAR}} v_{\omega}^{2} \tag{2.3}$$

where, ω_{ω} =Speed-up gear ratio,

η_{GEAR} =Turbine angular speed

λ = Tip speed ratio

The power coefficient is the figure-of-merit and is defined as the ratio of actual power delivered to the free stream power flowing through a similar but uninterrupted area, and tip speed

ratio (TSR) is the ratio of turbine speed at the tip of a blade to the free stream wind speed. The parameter is a nonlinear function of λ and is shown in result fig. 5.7. The oscillatory torque of the turbine is more dominant at the first, second, and fourth harmonics of fundamental turbine angular velocity and is given by the expression:

$$T_{OSC} = T_m(ACos(\omega_\omega t) + BCos(2\omega_\omega t) + CCos(4\omega_\omega t)) \qquad (2.4)$$

Where, A,B,C are the constants.

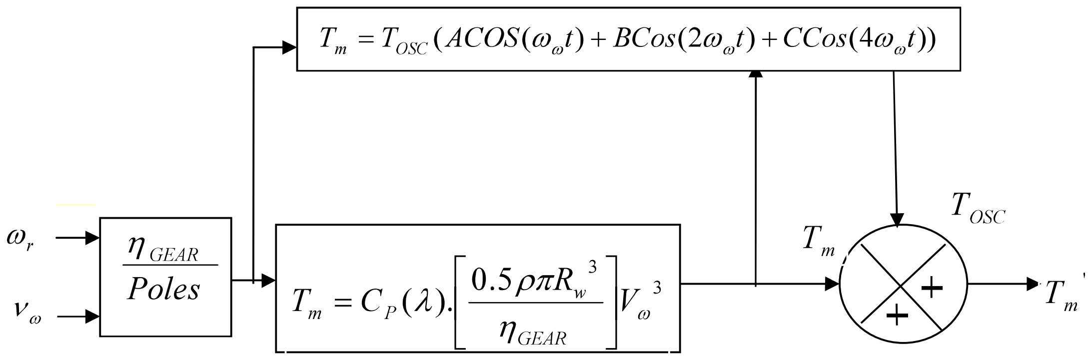

Fig.2.2 :Model of wind turbine with oscillatory torque

The turbine torque as a function of angular wind velocity is shown in result fig. 5.8.

2.1.3 Control System

The machine and inverter output currents are sinusoidal, as shown in fig.2.3. The machine absorbs lagging reactive current, but it is always zero on the line side; i.e., the line power factor is unity. The rectifier uses indirect vector control in the inner current control loop, whereas the direct vector control method is used for the inverter current controller. Vector control permits fast transient response of the system. The generator speed is controlled by indirect vector control with torque control and synchronous control in the inner loop.[1],[2] Since an increase of Po causes a decrease of DC link voltage, the voltage polarity loop has been reversed. For a particular wind velocity V_ω, there will be an optimum setting of generator speed ω_r* . The speed loop will generate the torque component of machine current so as to balance the developed torque with the load torque. The variable voltage variable frequency power from the super-synchronous induction generator will be rectified and pumped to the dc link. The dc link voltage controller will regulate the line power Po so that the link voltage always remains constant. A feed forward power signal from the machine output to the dc voltage loop prevents transient fluctuation of link voltage.

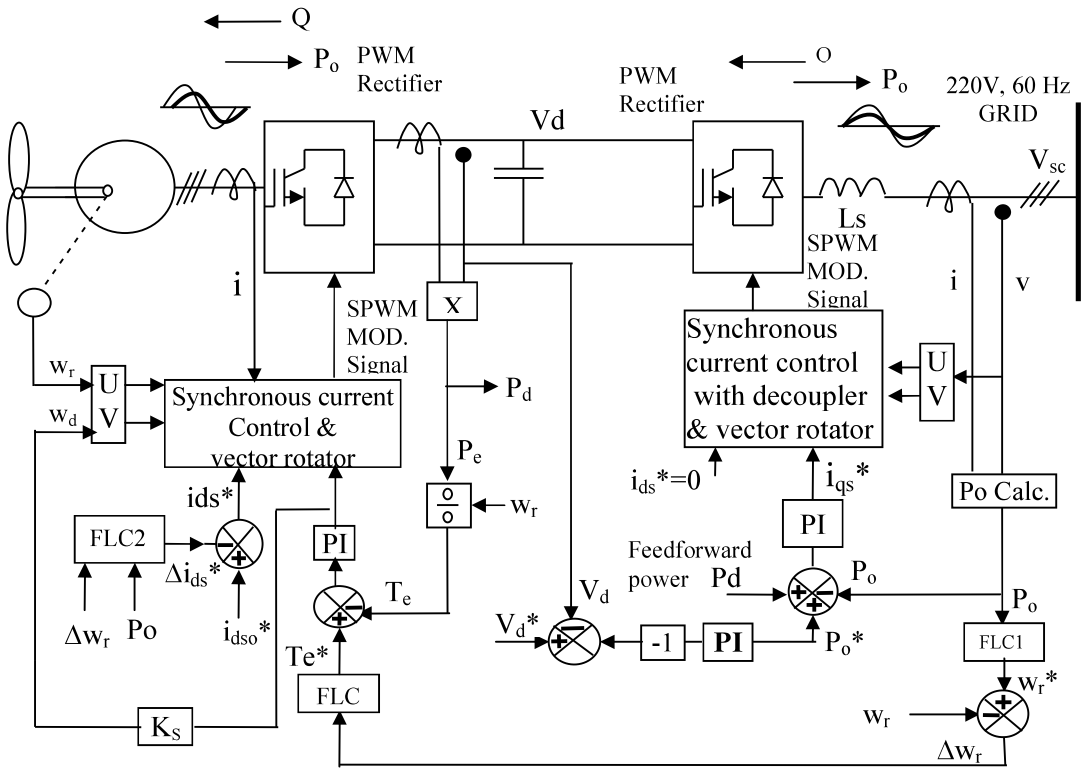

Fig.2.3:Fuzzy control FLC-1 and FLC-2 operation showing maximization of line power.

2.4 CONCLUSION

In this chapter basics wind generation system description has been covered . Also close loop control of the system has been discussed in brief.

CHAPTER 3

INDUCTION MACHINE

Dynamic d-q Model

Vector Control

Synchronous Current Control loop

Variable speed ac drives have been used in the past to perform relatively undemanding roles in application which preclude the use of dc motors, either because of the working environment or commutator limits. Because of the high cost of efficient, fast switching frequency static inverter, the lower cost of ac motors has also been a decisive economic factor in multi motor systems. However as a result of the progress in the field of power electronics, the continuing trend is towards cheaper and more effective power converters, and a single motor ac drives complete favorably on a purely economic basis with a dc drives.

Among the various ac drive systems, those which contain the cage induction motor have a particular cost advantage. The cage motor is simple and rugged and is one of the cheapest machines available at all power ratings. Owing to their excellent control capabilities, the variable speed drives incorporating ac motors and employing modern static converters and torque control can well complete with high performance four quadrant dc drives.

3.1 DYNAMIC d-q MODEL

R.H.Park in 1920's proposed a model for synchronous machine with respect to stationary ref frame. H.C.Stanley in 1930's proposed a model for induction machine with respect to stationary reference frame. Later G.Kryon's proposed a transformation of both stator and rotor variables to a synchronously rotating reference frame that moves with the rotating magnetic field. Lastly Krause and Thomas proposed a model for induction machine with respect to stationary reference frame.

3.1.1 Axes transformation

Consider a three phase induction machine with stationary stator winding axes as-bs-cs with voltages v_{as}, v_{bs}, v_{cs} and the stationary ref. frame are $d^s - q^s$ with voltages v_d^s, v_q^s.Let, v_{as} makes an angle θ with v_q^s.[12]Assume that the $d^s - q^s$ axes are oriented at an angle θ. The voltages $v_{ds}^s - v_{qs}^s$ can be resolved into as-bs-cs components :

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} Cos\theta & Sin\theta & 1 \\ Cos(\theta - 120^0) & Sin(\theta - 120^0) & 1 \\ Cos(\theta + 120^0) & Sin(\theta + 120^0) & 1 \end{bmatrix} \begin{bmatrix} v_{qs}^s \\ v_{ds}^s \\ v_{os}^s \end{bmatrix} \tag{3.1}$$

Taking inverse :

$$\begin{bmatrix} v_{qs}{}^{s} \\ v_{ds}{}^{s} \\ v_{os}{}^{s} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} Cos\theta & Cos(\theta-120^0) & Cos(\theta+120^0) \\ Sin\theta & Sin(\theta-120^0) & Sin(\theta+120^0) \\ 0.5 & 0.5 & 0.5 \end{bmatrix}\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} \tag{3.2}$$

The voltages on the $d^s - q^s$ can be converted into $d^e - q^e$ frame:

$$v_{qs} = v_{qs}{}^{s}Cos\theta_e - v_{ds}{}^{s}Sin\theta_e \tag{3.3}$$

$$v_{ds} = v_{qs}{}^{s}Sin\theta_e - v_{ds}{}^{s}Cos\theta_e \tag{3.4}$$

Resolving the rotating frame parameters into stationary frame:

$$v_{qs}{}^{s} = v_{qs}Cos\theta_e + v_{ds}Sin\theta_e \tag{3.5}$$

$$v_{ds}{}^{s} = -v_{qs}Sin\theta_e + v_{ds}Cos\theta_e \tag{3.6}$$

Let , $v_{as} = V_m Cos(\omega_e t + \phi)$ (3.7)

$$v_{bs} = V_m Cos(\omega_e t - \frac{2\pi}{3} + \phi) \tag{3.8}$$

$$v_{cs} = V_m Cos(\omega_e t + \frac{2\pi}{3} + \phi) \tag{3.9}$$

From equation :

$$v_{qs}{}^{s} = V_m Cos(\omega_e t + \phi) \tag{3.10}$$

$$v_{ds}{}^{s} = -V_m Sin(\omega_e t + \phi) \tag{3.11}$$

From equation

$$v_{qs} = V_m Cos\phi \tag{3.12}$$

$$v_{ds} = -V_m Sin\phi \tag{3.13}$$

This shows that the sinusoidal variables in a stationary frame appear as DC quantity.

$$|\overline{V}| = V_m \tag{3.14}$$

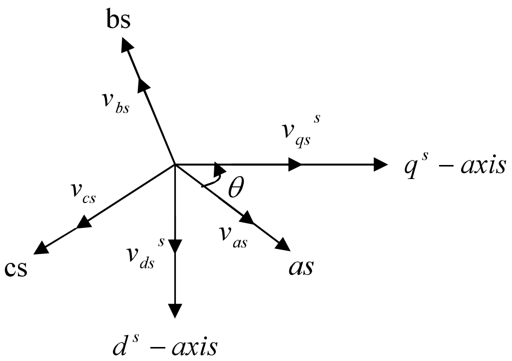

Fig.3.1 :Stationary frame a-b-c to d^s-q^s axes transformation

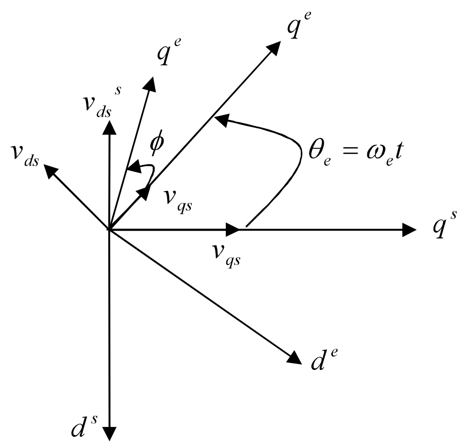

Fig.3.1 : Stationary frame d^s-q^s to synchronously rotating frame d^e-q^e

3.1.2 Synchronously rotating ref frame-Dynamic model (Kron's equation)

The stator circuit equations are:

$$v_{qs}^{s}=R_s i_{qs}^{s}+\frac{d}{dt}\psi_{qs}^{s} \tag{3.15}$$

$$v_{ds}^{s}=R_s i_{ds}^{s}+\frac{d}{dt}\psi_{ds}^{s} \tag{3.16}$$

Where, $\psi_{qs}^{s}=$ q axis flux linkage

$\psi_{ds}^{s}=$ d axis flux linkage

$$v_{qs}=R_s i_{qs}+\frac{d}{dt}\psi_{qs}+\omega_e\psi_{ds} \tag{3.17}$$

$$v_{ds}=R_s i_{ds}+\frac{d}{dt}\psi_{ds}-\omega_e\psi_{qs} \tag{3.18}$$

If the rotor is not rotating, the rotor equations will be written as:

$$v_{qr} = R_r i_r + \frac{d}{dt}\psi_{qr} + \omega_e \psi_{dr} \tag{3.19}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_e \psi_{qr} \tag{3.20}$$

If rotor rotates,then the equation will be:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr} \tag{3.21}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr} \tag{3.22}$$

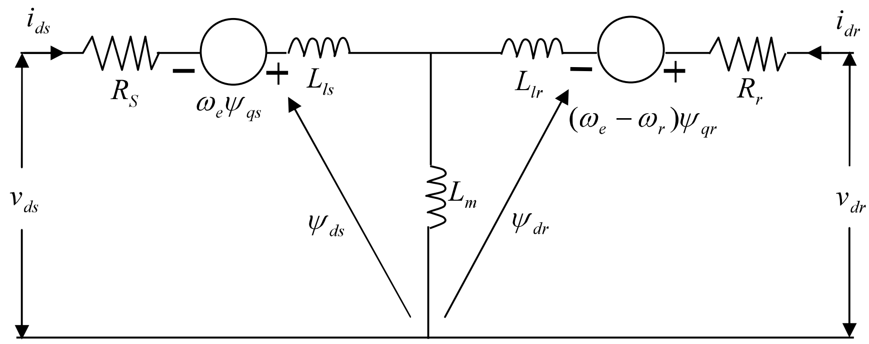

Fig. 3.2 : Dynamic d^e axis circuit

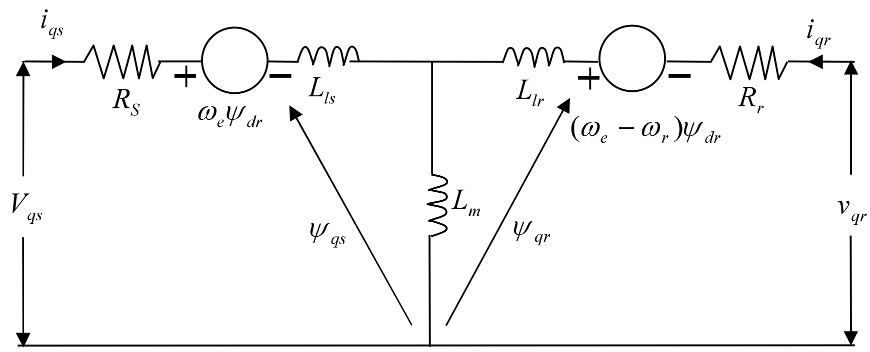

Fig. 3.3 : Dynamic q^e axis circuit

The flux linkage expressions in terms of the circuit currents are :

$$\psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) \tag{3.23}$$

$$\psi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) \tag{3.24}$$

$$\psi_{qm} = L_m (i_{qs} + i_{qr}) \tag{3.25}$$

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) \tag{3.26}$$

$$\psi_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) \tag{3.27}$$

$$\psi_{dm} = L_m (i_{ds} + i_{dr}) \tag{3.28}$$

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + SL_s & \omega_e L_s & SL_m & \omega_e L_m \\ -\omega_e L_s & R_s + SL_s & -\omega_e L_m & SL_m \\ SL_s & (\omega_e - \omega_r) L_m & R_r + SL_r & (\omega_e - \omega_r) L_r \\ -(\omega_e - \omega_r) L_m & SL_m & -(\omega_e - \omega_r) L_r & R_r + SL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \tag{3.29}$$

The torque is given by:

$$T_e = \frac{3}{2} \left(\frac{P}{2} \right) \psi_m \times I_r \tag{3.30}$$

3.2 VECTOR CONTROL

Scalar control is simple to implement but its inherent coupling effect gives sluggish response and system is easily prone to instability. So vector control is advantageous over scalar control.

3.2.1 DC drive analogy

A vector controlled induction motor drive operates like a separately excited DC motor[12].In D C machine , neglecting the armature reaction effect and field saturation , the developed torque is given by:

$$T_e = K_t' I_a I_f \tag{3.31}$$

Where, I_a=armature current

I_f=Field current

The space vectors which are stationary in space, are orthogonal or decoupled in nature.

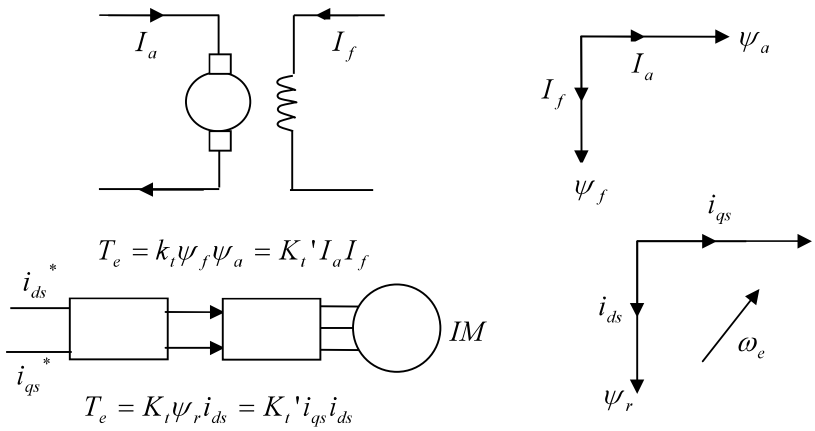

Fig. 3.4 : (a) separately excited DC motor , (b) Vector controlled induction motor

3.3 SYNCHRONOUS CURRENT CONTROL LOOP

The command current $i_{ds}*, i_{qs}*$ in the vector control are compared with the respective i_{ds}, i_{qs} currents generated by the transformation of phase current with the help of unit vector[12]. The respective errors generates the voltage command signals $v_{ds}*, v_{qs}*$ through PI compensators. These voltage commands are then converted into stationary frame phase voltages. The synchronous frame current control with a PI controller assure amplitude and phase tracking of currents, even when the PWM goes into over modulation range.

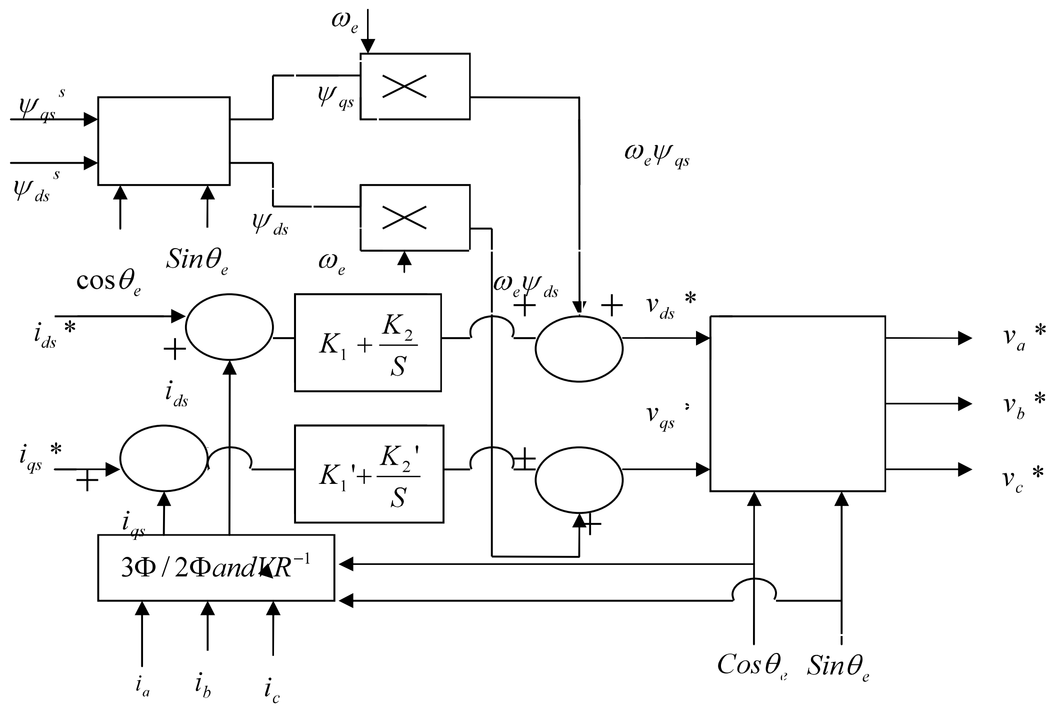

Fig. 3.5 : Synchronous current control loop

3.4 CONCLUSION

This chapter deals with basics of dynamic d-q model, vector control and synchronous current control loop of induction machine .

CHAPTER 4

FUZZY LOGIC AND FUZZY LOGIC CONTROLLER

Fuzzy logic is the methodology for the handling of inexact, imprecise, qualitative, fuzzy, verbal in-formation in a systemic and rigorous way.

Fuzzy logic is used in power electronics due to the following reasons :

- Parameter variations that can be compensated with designer judgement.
- Processes that can be modeled linguistically but not mathematically.
- Setting with the aim to improve efficiency as a matter of operator skill and attention.
- When the system depends on operator skills and attention.
- Whenever one process parameter affects another process parameter.
- Effects that cannot be attained by separate PID control.
- Whenever a fuzzy controller can be used as an advisor to the human operator.
- Data intensive modeling .

4.1 FUZZY LOGIC CONTROL

The heuristic way of seaching the maximum could be based on a rule called as "Fuzzy Meta- rule", which is given as follows:

"If the last change in the input variable (x) has caused the output variable (y) to increase ,keep moving the input variable in the same direction; if it has caused the output variable to drop, move it in the opposite."

The Wind generation system consists of three no.s of fuzzy logics:

4.1.1 Generator speed tracking control (FLC-1)

Since the power is given by the product of torque and speed and turbine power equals the line power (assuming steady state lossless system), the turbine torque/speed curves can be translated to line power ~ generator speed curves. For a particular value of wind velocity, the function of fuzzy controller FLC-1 is to search the generator speed until the system settles down at the maximum output power condition. For wind velocity ω_{r4} of the output power will be at A if the generator speed is $V_{\omega 4}$. The FLC-1 will alter[1],[8] the speed in steps until it reaches the Speed ω_{r1} , where the output power is maximum at B . If the wind velocity increases to $V_{\omega 2}$, the output power will jump to D, and then FLC-1 will bring the operating point to E by searching the speed to ω_{r2} . With an incrementation (or decrementation) of speed, the corresponding incrementation (or decrementation) of output power is estimated. The controller operates on a per-unit basis so that the response is insensitive to system variables and the algorithm is universal to any system.. The wind vortex and torque ripple can lead the search to be trapped in a minimum which is not global, so the output $\Delta\omega_r$ is added to some amount of $L\Delta\omega_r$ in order to give some momentum to continue the search and to avoid such local minima[10]. The controller operates on a per-unit basis so that the response is insensitive to system variables and the algorithm is universal to any system. The scale factors KPO and KWR , are generated as a function of generator speed so that the control becomes somewhat insensitive to speed variation. The scale factor expressions are given, respectively, as:

$$KPO = a_1\omega_r \tag{4.1}$$

$$KWR = a_2\omega_r \tag{4.2}$$

Where a_1 and a_2 are the constant coefficients that are derived from simulation studies.

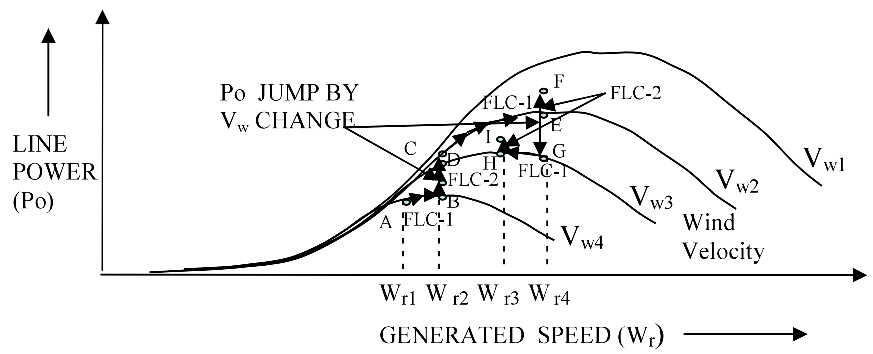

Fig.4.1:Fuzzy control FLC-1 and FLC -2 operation showing maximization of line power.

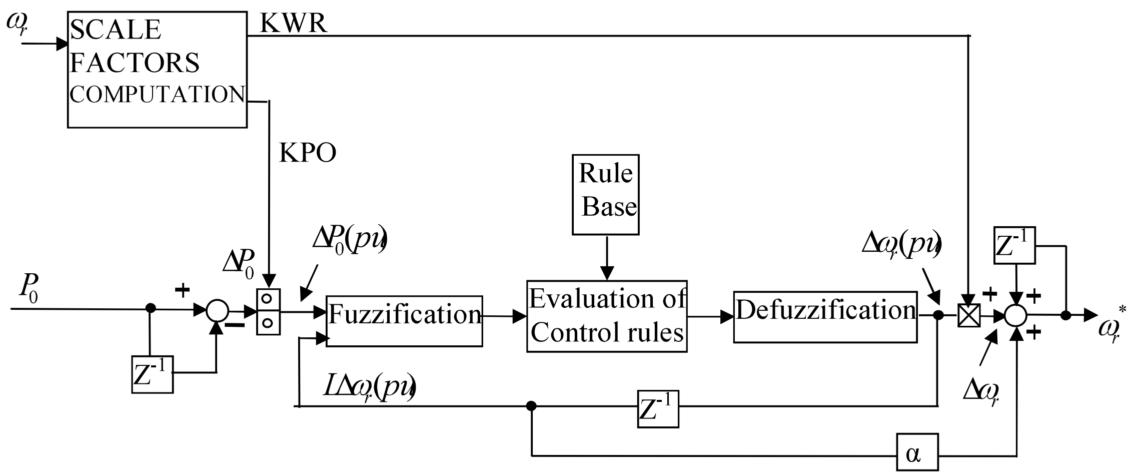

Fig. 4.2: Block diagram of fuzzy control FLC-1

In FLC-1, there are two inputs ΔP0 and L$\Delta\omega_r^*$ and one output $\Delta\omega_r^*$ .In the implementation of fuzzy control, the input variables are fuzzified ,the valid control rules are evaluated and combined and finally the output is defuzified to convert to the crispy value. The rule matrix is given in table 1.

In this thesis , the above block diagram of FLC-1 was simulated using triangular membership function and the centroid method was used for defuzzification.

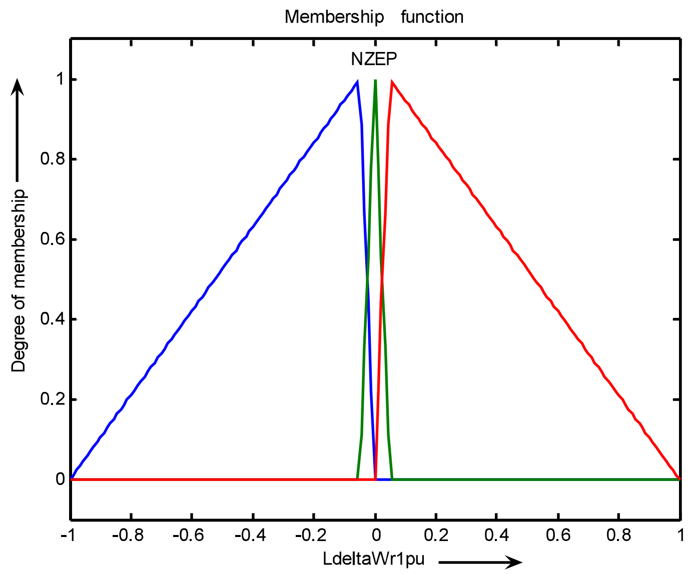

Fig. 4.3 (a)

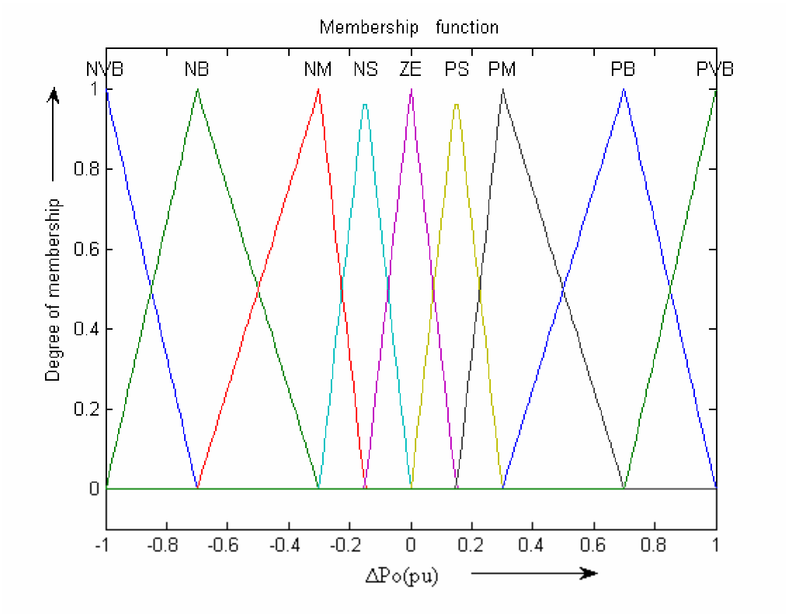

Fig.4.3(b)

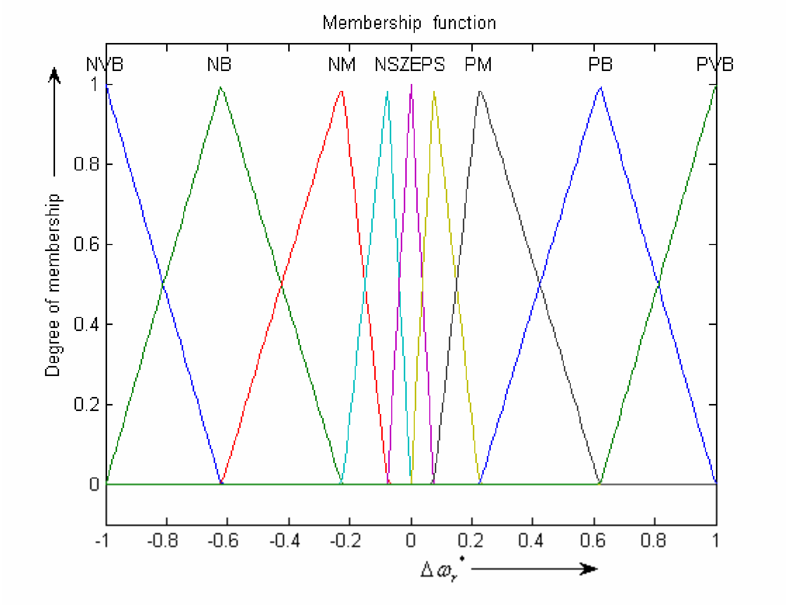

Fig.4.3(c)

Fig.4.3: Membership functions of FLC-1

The membership functions for all the variables are asymmetrical [2],[5] because they gives more sensitivity as the variables approaches zero value.

The rule matrix for FLC-1[2],[11] is given below:

$L\Delta\omega_r^*$ / ΔP_0	P	ZE	N
NVB	NVB	NVB	PVB
NB	NB	NVB	PB
NM	NM	NB	PM
NS	NS	NM	PS
ZE	ZE	ZE	ZE
PS	PS	PM	NS
PM	PM	PB	NM
PB	PB	PVB	NB
PVB	PVB	PVB	NVB

Table 1: Rule matrix for FLC-1

A typical rule can be read as follows:

"If ΔPo is PM (positive medium) AND $L\Delta\omega_r^*$ is P (positive) , THEN $\Delta\omega_r^*$ is PM (positive medium)."

The controller operates on per unit basis so that the response is insensitive to the system variables.

4.1.2 Generator flux programming control (FLC-2)

The system output power $Po(k)$ is sampled and compared with the previous value $Po(k-1)$ to determine the increment ΔPo. In addition, the last excitation current decrement $L\Delta i_{ds}$ is reviewed. On these bases, the decrement step of i_{ds} is generated from fuzzy rules through fuzzy inference and defuzzification . It is necessary to process the inputs of FLC-2 in per-unit values [1],[9]. Therefore, the adjustable gains KP and KIDS convert the actual variable to variables with the following expressions:

$$KP = a\omega_r + b \tag{4.3}$$

$$KIDS = C_1\omega_r - C_2 i_{qs} + C_3 \tag{4.4}$$

Where a, b,C_1 ,C_2 and C_3 are derived from simulation studies.

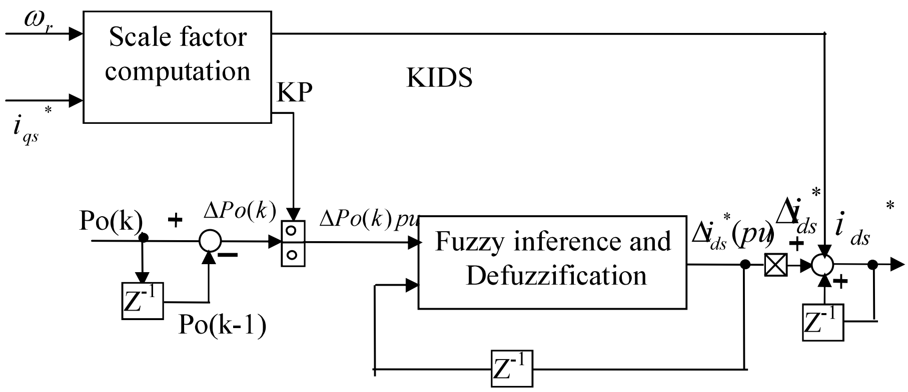

Fig. 4.4 : Block diagram of fuzzy control FLC-2

The membership function of various variables for FLC-2 are found to be:

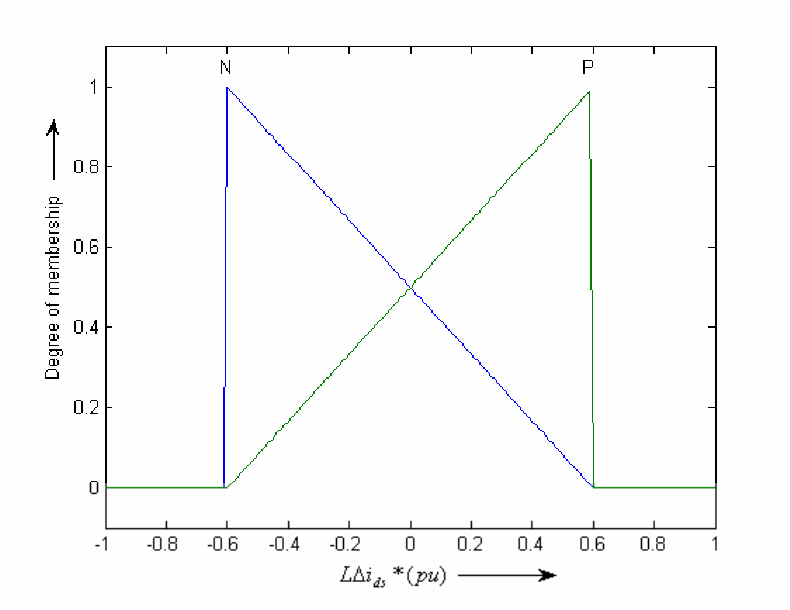

Fig.4.5(a)

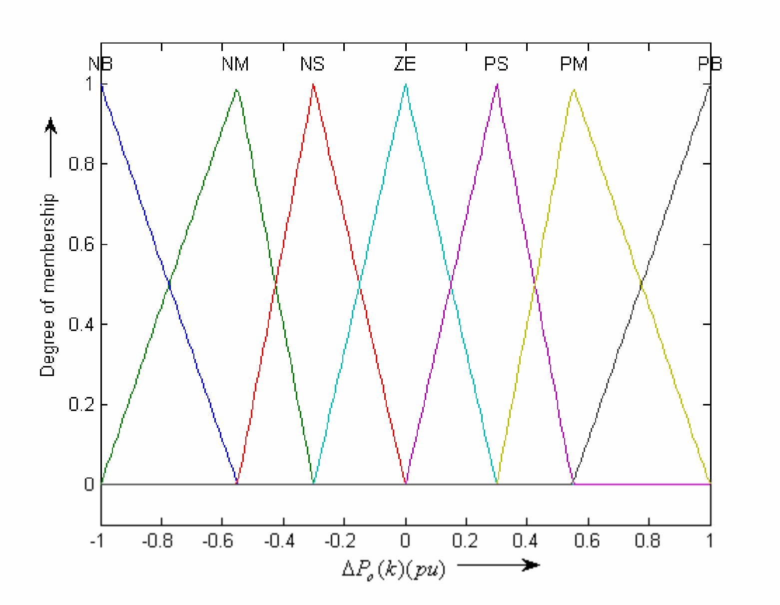

Fig.4.5(b)

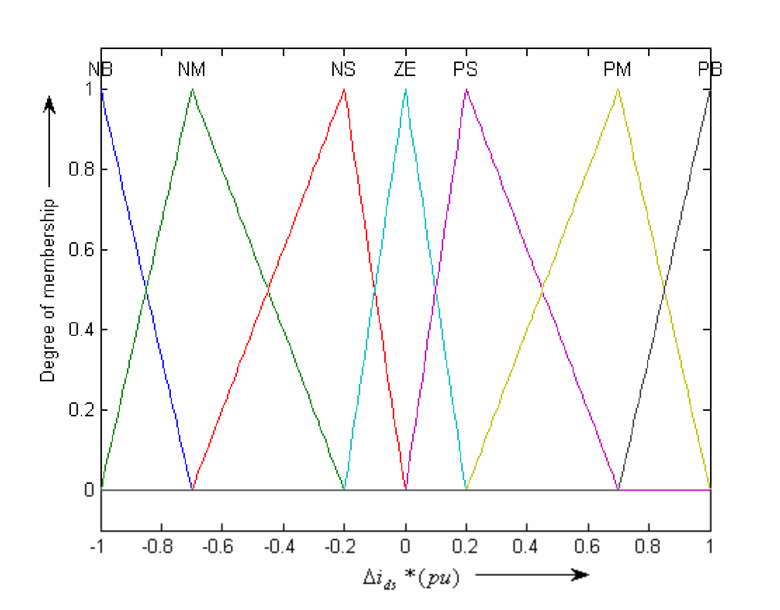

Fig.4.5(c)

The rule matrix for FLC-2 [2],[11] is given below:

$L\Delta i_{ds}$*(pu) ΔP_0(k)	N	P
PB	NM	PM
PM	NS	PS
PS	NS	PS
NS	PS	NS
NM	PM	NM
NB	PB	NB

Table 2: Rule matrix for FLC-2

A typical rule can be read as follows :

"If ΔPo(k) is PM (positive medium) AND $L\Delta i_{ds}$* is P (positive) , THEN Δi_{ds}* is PS (positive small)."

4.1.3 Closed loop generator speed control (FLC-3)

The speed loop error $E\omega_r$* and error change $\Delta E\omega_r$* signals are converted to per-unit signals, processed through fuzzy control, and then summed to produce the generator torque component of current Δ i_{qs}* .It has to be noted that while fuzzy controllers FLC-1 and FLC-2 operate in sequence at steady wind velocity, FLC-3 is always active during system operation.

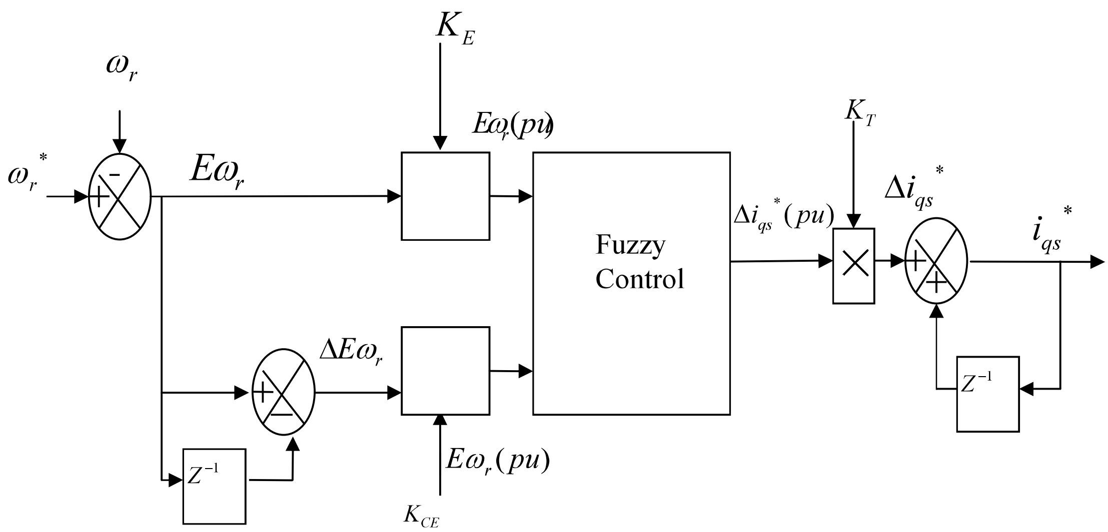

Fig. 4.6 : Block diagram of fuzzy control FLC-3

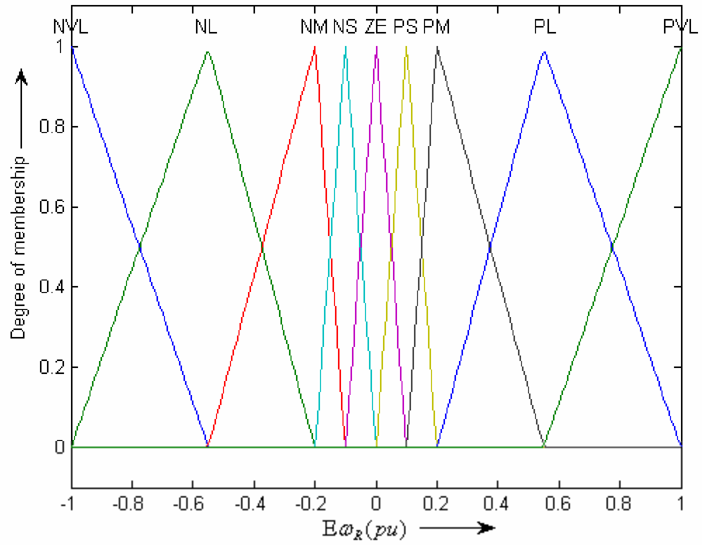

Fig.4.7(a)

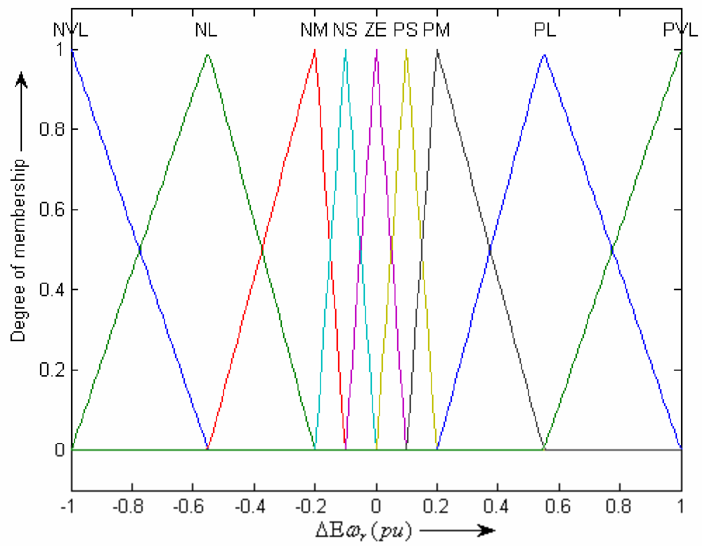

Fig.4.7(b)

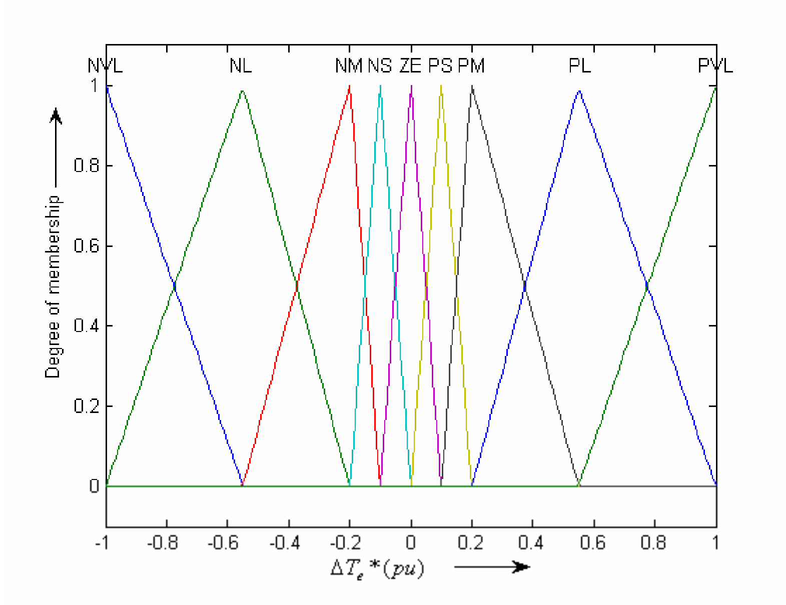

Fig.4.7(c)

Fig.4.7 : Membership functions of FLC-3

The rule matrix for FLC-3 [2],[11] is as follows:

$E\omega_r$(pu) $\Delta E\omega r$(pu)	NVL	NL	NM	NS	ZE	PS	PM	PL	PVL
NVL					NVL	NL	NM	NS	ZE
NL					NL	NM	NS	ZE	PS
NM				NL	NM	NS	ZE	PS	PM
NS			NL	NM	NS	ZE	PS	PM	PL
ZE		NL	NM	NS	ZE	PS	PM	PL	
PS	NL	NM	NS	ZE	PS	PM	PL		
PM	NM	NS	ZE	PS	PM	PL			
PL	NS	ZE	PS	PM	PL				
PVL	ZE	PS	PM	PL	PVL				

Table 3:Rule matrix for FLC-3

A typical rule is read as follows :

"If error $E\omega_r$(pu) is PM (positive medium) AND change in error $\Delta E\omega_r$(pu) is PS (positive small) , THEN the torque increment ΔT_e*(pu) is PL (positive large)."

4.9 CONCLUSION

In this chapter all the three fuzzy logic controllers with their rule matrices has been discussed.

- The first fuzzy controller FLC-1 searches on line the optimum generator speed so that the aerodynamic efficiency of the wind turbine is maximum.
- The second fuzzy controller FLC-2 programs the machine flux by an on line search so as to optimize the machine converter efficiency.
- The third fuzzy controller FLC-3 performs robust speed control against turbine turbine oscillatory torque and wind vortex.

The membership functions of the fuzzy - variables and the rule matrix were extensively iterated by simulation until the performance was found to be better.

CHAPTER 5

SIMULATION - RESULTS AND DISCUSSIONS

5.1 OPEN LOOP SIMULATION OF 3 –PHASE INDUCTION MOTOR

5.1.1 Torque ~ speed

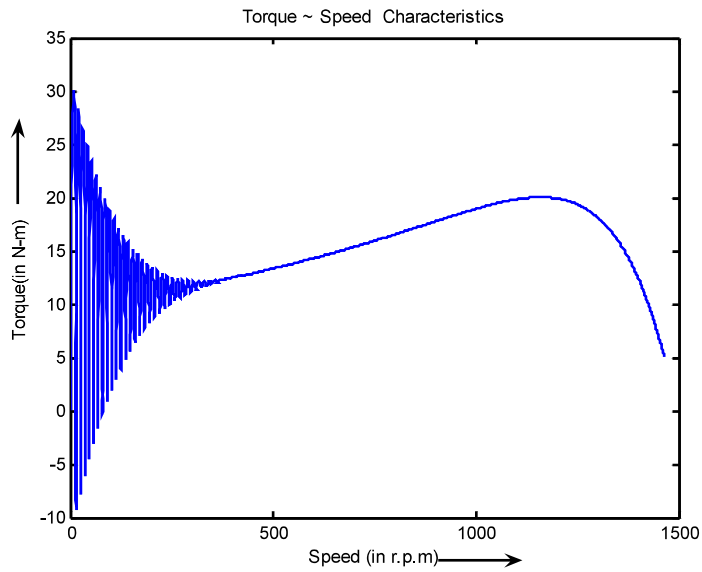

Fig . 5.1 : Torque ~ speed characteristics

5.1.2 i_{ds} ~ time

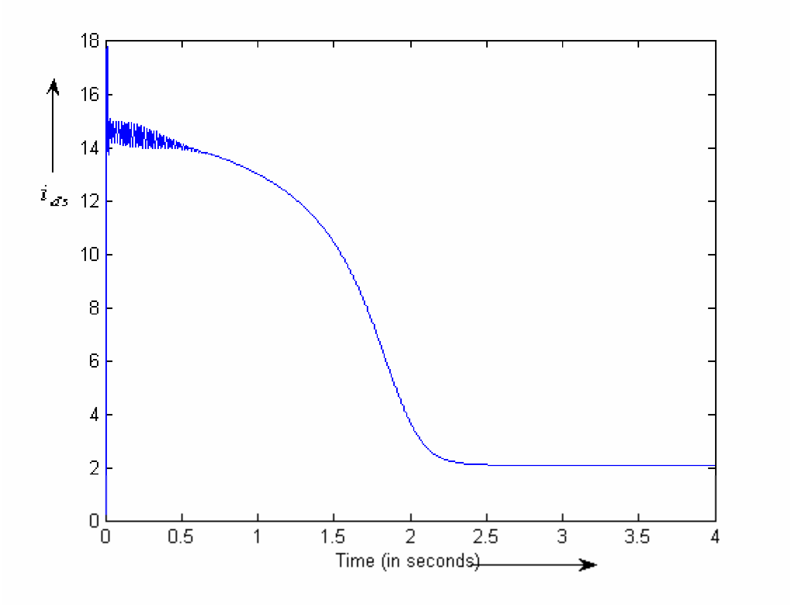

Fig. 5.2 : i_{ds} ~ time

5.1.3 i_{qs} ~ time

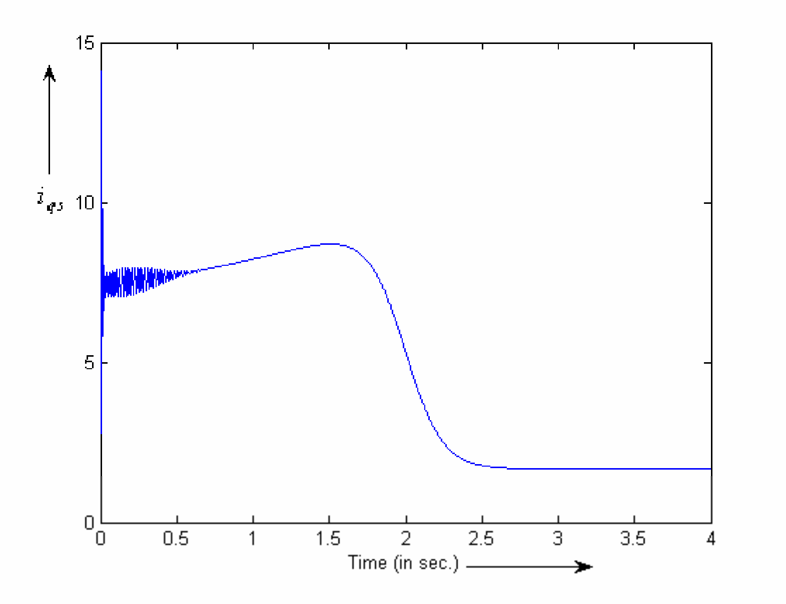

Fig.5.3 : i_{qs} ~ time

5.1.4 ψ_{dr} ~ time

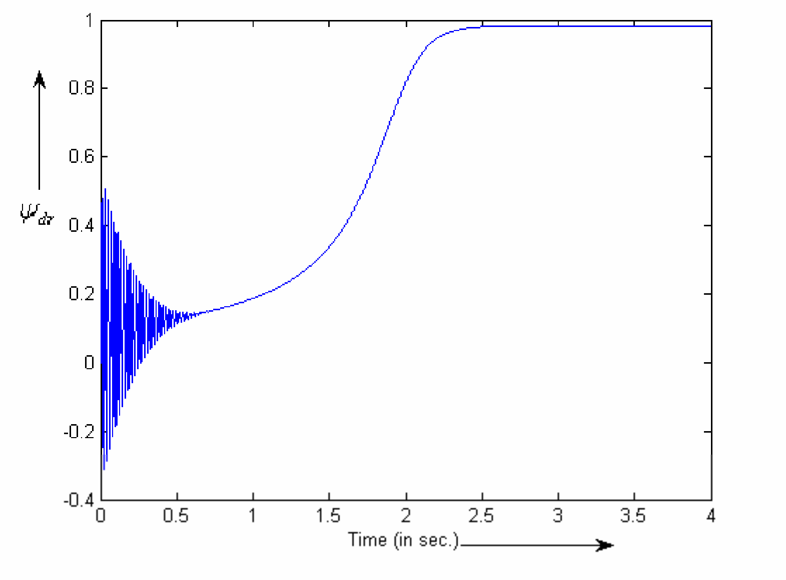

Fig .5.4 : ψ_{dr} ~ time

5.1.5 $\psi_{qr} \sim$ time

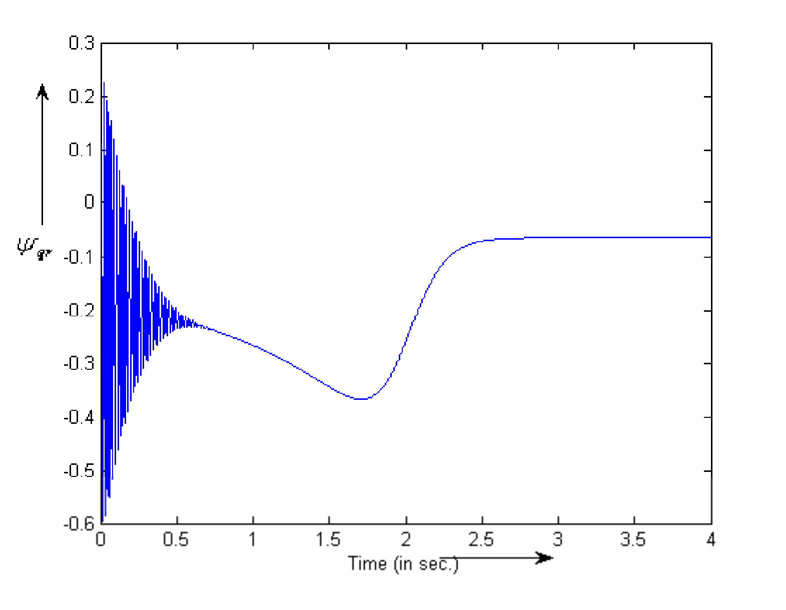

Fig. 5.5 : $\psi_{qr} \sim$ time

5.2 Open loop simulation (Torque ~ speed) of induction generator connected to wind Turbine

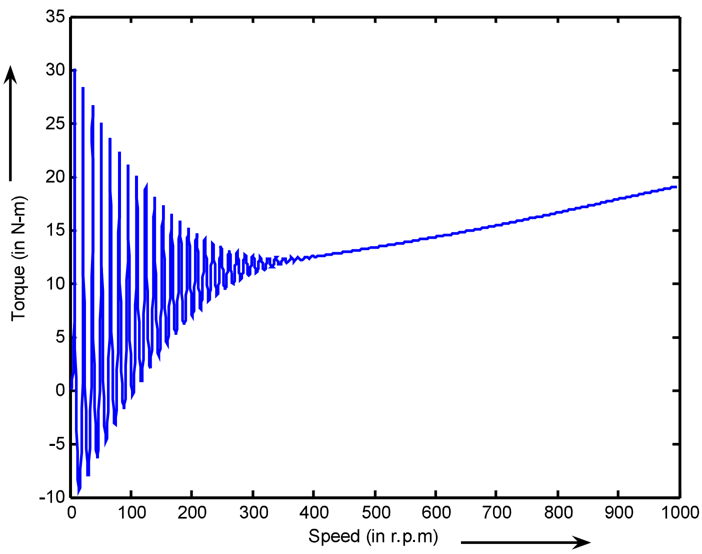

Fig. 5.6 : Torque ~ speed characteristics

5.3 $C_P \sim \lambda$ Characteristics

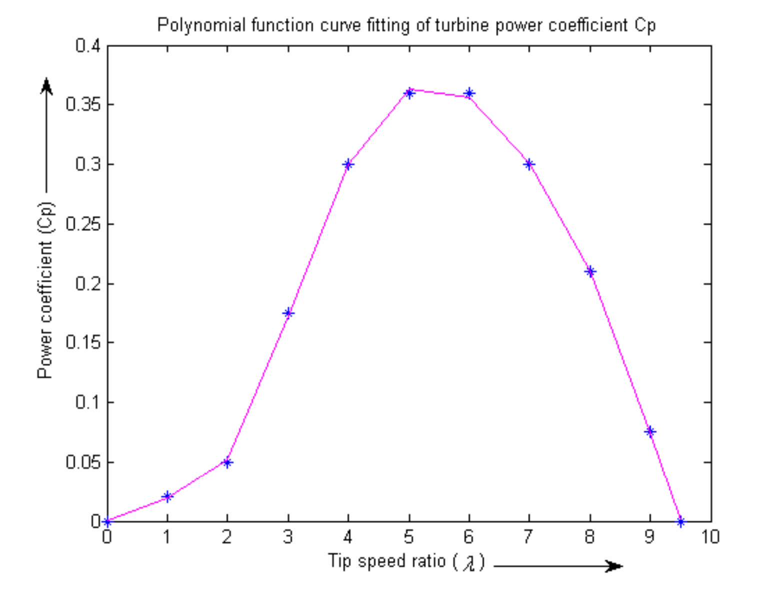

Fig.5.7 : $C_P \sim \lambda$ Characteristics

5.4 Turbine torque ~ turbine angular speed

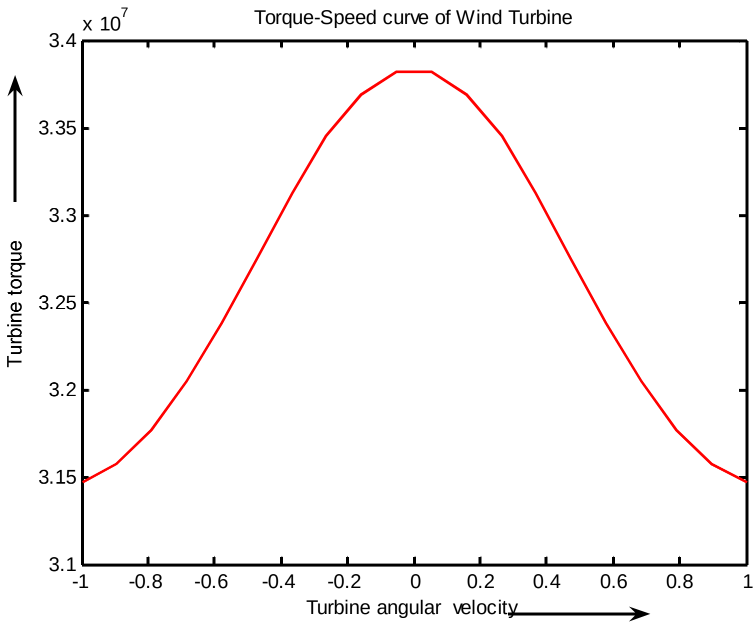

Fig. 5.8 : Turbine torque – turbine angular speed

5.5 TURBINE AND SYSTEM MODEL SIMULATION CURVES

5.5.1 Turbine developed torque ~ turbine angular speed

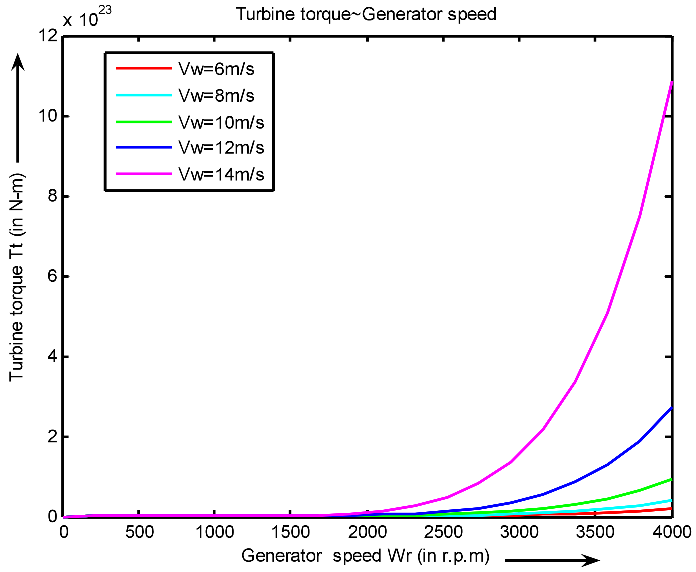

Fig. 5.9 : Turbine developed torque ~ turbine angular speed

5.5.2 Turbine developed power ~ turbine angular speed

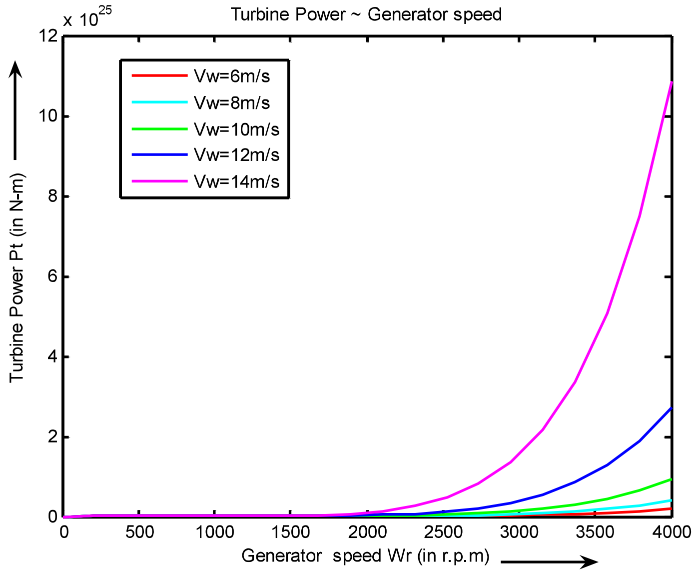

Fig. 5.10 : Turbine developed power ~ turbine angular speed

5.5.3 Line side generated power ~ turbine angular speed

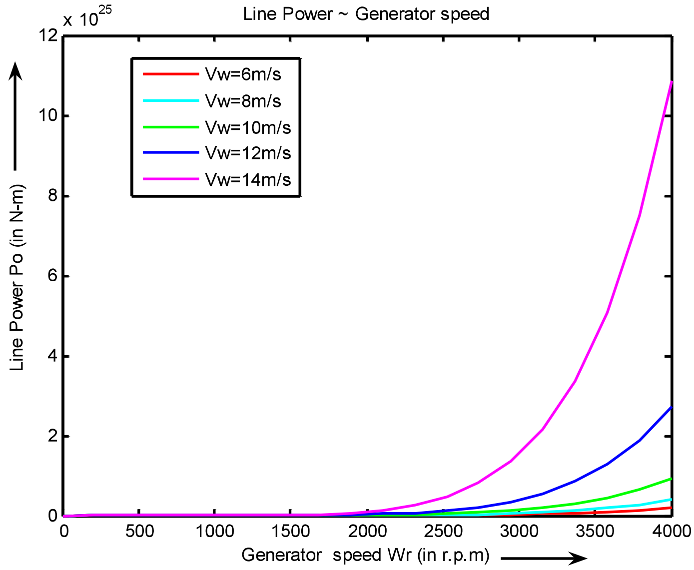

Fig. 5.11 : Turbine developed power ~ turbine angular speed

5.6 Time domain operation of fuzzy controls FLC-1 , FLC-2 and FLC -3

5.6.1 Wind velocity ~ time

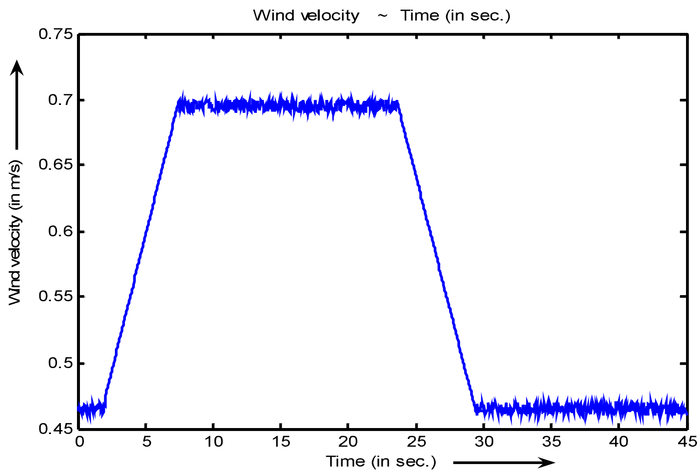

Fig. 5.12 : Wind velocily ~ Time (in Sec.)

5.6.2 Generator speed ~ time

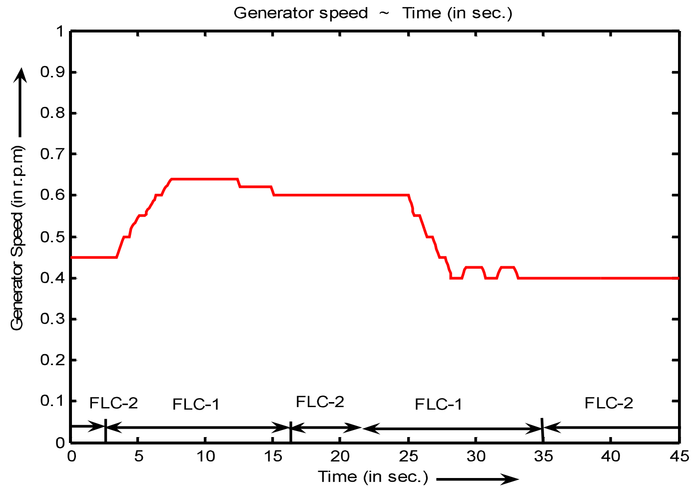

Fig. 5.13 : Generator speed ~ Time (in sec.)

5.6.3 Flux current ~ time

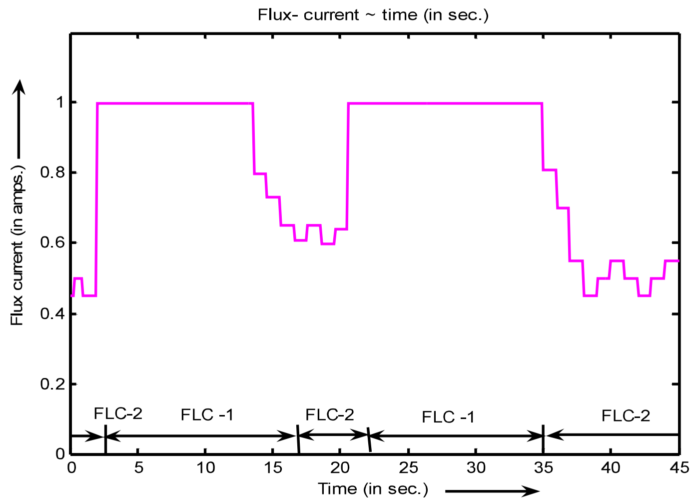

Fig. 5.14 : Generator speed ~ Time (in sec.)

5.6.4 Output power ~ time

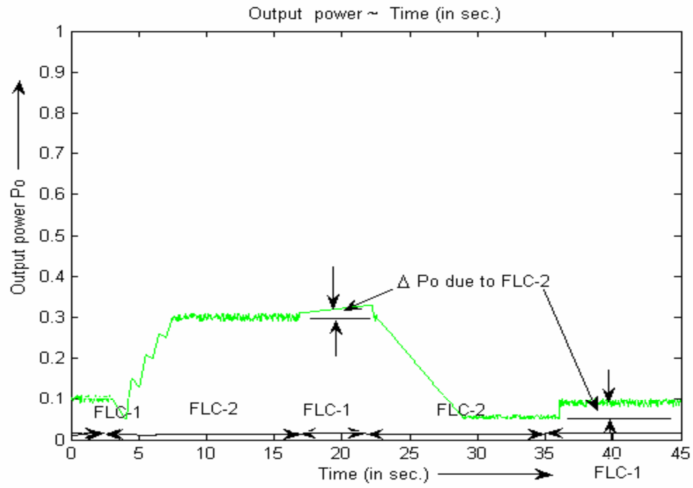

Fig. 5.15 : Output power ~ Time (in sec.)

Discussions :

Fig.5.1 : When the induction motor is started , initially it shows transients and this region of operation is called as unstable region of operation. After some time torque increases and a steady state is reached. This region of operation is called as stable region of operation.

Fig.5.2 : Initially i_{ds} shows transients, it then decreases drastically and finally reaches a steady state value.

Fig.5.3: Initially i_{qs} shows transients,it then increases but after some time it decreases drastically and finally a steady state is reached.

Fig.5.4: Initially ψ_{dr} shows transients and after some time it increases drastically . Finally it reaches a steady state value.

Fig.5.5: Initially ψ_{qr} shows transients and after some time it decreases slightly and then increases and finally it reaches a steady state value.

Fig.5.6: It is the open loop simulation result of induction generator connected to wind turbine. Initially it shows transients and this region of operation is called as unstable region of operation. After some time torque increases and a steady state is reached. This region of operation is called as stable region of operation.

Fig.5.7: The turbine power coefficient C_P is the figure-of-merit and is defined as the ratio of actual power delivered to the free stream power flowing through a similar but uninterrupted area, and tip speed ratio (λ) is the ratio of turbine speed at the tip of a blade to the free stream wind speed. The parameter C_P is a nonlinear function of λ .

From [1], the power coefficient C_P as a polynomial function of λ can be represented as :

$$y = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6 + hx^7 \qquad (6.1)$$

Where, a,b,c,d,e,f,g,h are all constants , whose values have been taken from [1].

This fig reveals that turbine power coefficient C_P is a non – linear function of tip speed ratio λ.

Fig.5.8: From [1] , total turbine torque is the sum of aerodynamic torque and Oscillatory torque of turbine .

This results reveals the torque speed characteristic of wind turbine when the turbine runs in both forward and reverse direction.. The torque follows a square law characteristic, whi9ch shows that at light load steady state conditions, generator efficiency can be improved by programming flux [6].

Fig.5.9: This result reveals that for a particular generator speed , if the wind velocity is increased , its corresponding turbine torque is also increased. It can be noted here that for simplicity, the turbine oscillatory torques are ignored in the system result.

Fig.5.10: As we know that power is torque multiplied with speed. So, fig. 5.10 will be same as fig. 5.9. This result reveals that for a particular generator speed , if the wind velocity is increased , its corresponding turbine developed power is also increased. It can be noted here that for simplicity, the turbine oscillatory torques are ignored in the system result.

Fig.5.11: The system was assumed to be a lossless system, it can be said that the turbine developed power is equal to the line side power. This result reveals that for a particular generator speed , if the wind velocity is increased , its corresponding line side power is also increased. It can be noted here that for simplicity, the turbine oscillatory torques are ignored in the system result.

Fig.5.12 – Fig.5.15:

The fig.5.12 has been taken as the input for obtaining closed loop response of the wind generation system. With respect to the change in the wind velocity , the outputs are observed and are shown with the help of fig.5.13- fig.5.15 .Now here the turbine is modeled with turbine oscillatory torque (T_{OSC}) and some turbulence has also been added with the wind velocity to verify the robustness of FLC-3. Fig. 5.13- fig.5.15 shows the performance of the system with FLC-1 , FLC-2 and FLC-3 when the wind velocity is ramped up and down It can be observed here that as the generator speed is increased by FLC-1.

As the generator speed is increased by FLC-1, the line output power gradually increases, but the line power indicates some dips. As generator speed command is incremented by FLC-1, the machine accelerates to the desired speed with the power extracted from the turbine output power. As a result, line power temporarily sags until boosted by the turbine power at steady state. With a large increment of speed command, the direction of Po can even reverse. In order to prevent such conditions, the maximum speed command increment was limited to a reasonably small value (75 RPM) and had a ramp shape. The slope of the ramp can be adjusted to control the power dips. It can be noted that the speed command decrement will have an opposite effect; i.e., the generator tends to decelerate, giving bumps in the output power.

CHAPTER 6

CONCLUSION

CONCLUSION

FUTURE WORK

6.1 CONCLUSION

The fuzzy logic based variable speed cage machine wind generation system was studied and analyzed. The system performances was studied by simulation to validate all the theoretical concepts.

There are three fuzzy logic controllers in the generation system :

- The first fuzzy controller FLC-1 searches on line the optimum generator speed so that the aerodynamic efficiency of the wind turbine is maximum.
- The second fuzzy controller FLC-2 programs the machine flux by an on line search so as to optimize the machine converter efficiency.
- The third fuzzy controller FLC-3 performs robust speed control against turbine turbine oscillatory torque and wind vortex.

The main conclusions of this thesis are :

- The system was found to be parameter insensitive with fuzzy controllers.
- The system shows a fast-convergence with fuzzy controllers.
- The system can accepts noisy and inaccurate signals.
- The fuzzy algorithms used in the system are universal and can be applied retroactively in any other system.
- The performance of the system was found to be excellent with all the fuzzy logic controllers.

6.2 FUTURE WORK

The following are the areas of future study which should be considered for further research work :

- Application of neural network controller for maximum power extraction of a grid-connected wind turbine system.
- Energy flow and management of a hybrid wind/PV/fuel cell generation system.
- Systematic Evaluation of Harmonic and inter-harmonic Measurements of wind Energy Systems.
- Fuzzy -logic pitch angle controller for power system stabilization of wind generation system.

APPENDIX

DETERMINATION OF PARAMETERS :

A 3 - phase squirrel cage induction motor with following specifications was considered for experimental work.:

SPECIFICATIONS : 3-Phase, 3.7 KW, 415 V,7.5 A, 1445 r.pm.,50 Hz, Delta connected, Efficiency 84%, Sq. Cage type induction motor.

The no-load test, blocked rotor test, D.C stator resistance test and retardation test were conducted and lastly following parameters have been obtained :

Sl. No.	Parameters calculated	Calculated value
1.	Lm (Magnetizing inductance)	0.5 H
2.	Lo (No load stator inductance)	0.53 H
3.	Ls (Stator inductance)	0.53 H
4.	Xbr(Blocked rotor inductance)	13.921 Ohms
5.	X (Stator inductive reactance)	6.96 Ohms
6.	X (Rotor inductive reactance as ref. to stator)	6.96 Ohms
7.	(R Delta)ac (A.C Stator resistance)	11.66 Ohms
8.	J (Moment of Inertia)	0.174 Kg-meter sq.
9.	B(Viscous frictional constant)	0.033 N-m / rad per sec

Table: Calculated parameters

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